AD-A196 009

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT
	Approved for public release and sale.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	Distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
ONR Technical Report No. 1	

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
UNIVERSITY OF WYOMING		Office of Naval Research Resident Representative

6c. ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
DEPARTMENT OF CHEMISTRY UNIVERSITY OF WYOMING LARAMIE WY 82071-3838	University of New Mexico Bandelier Hall West Albuquerque, NM 87131

8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
Office of Naval Research	ONR	N00014-87-K-0674

8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. R & T	WORK UNIT ACCESSION NO
800 N. Quincy Street Arlington, VA 2217			41330190	

11. TITLE (Include Security Classification)

(u) Mass Measurements Using Isotopically Labeled Solvents Reveal the Extent of Solvent Transport During Redox in Thin Films on Electrodes

12. PERSONAL AUTHOR(S) Steven J. Lasky and Daniel A. Buttry*

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 9/87 TO 6/88	1988 July 6	9

16. SUPPLEMENTARY NOTATION

Prepared for publication in the Journal of the American Chemical Society

17	COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	electrochemistry, quartz crystal microbalance, modified electrode

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
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DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted.
All other editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

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Transport of solvent during the redox reactions of thin films on electrodes has been identified as a possible influence on both the thermodynamic and kinetic aspects of their electrochemical responses (1). A variety of methods has been used in attempts to measure solvent content of these films, including ellipsometry (2,3) and profilimetry (4). However, those techniques which rely on measurement of thickness suffer from inability to deconvolute the contributions to swelling (or deswelling) from ion and solvent transport. Thus, the situation remains one in which speculation abounds, but accurate measurements are unavailable. In this Communication, we report on the application of the quartz crystal microbalance (QCM) technique to the determination of solvent transport during redox in thin films of nickel ferrocyanide (the nickel analog of Prussian Blue (5-12)) by comparing the difference in the total mass change (comprised of contributions from both ion and solvent transport) which results from use of isotopically substituted solvent. To our knowledge, these experiments represent the first accurate, unambiguous measurements of solvent transport in thin films on electrodes. It is especially significant that these measurements are made in the presence of simultaneous ion transport.

The QCM apparatus has been previously described (13-15). When used in conjunction with electrochemical measurements, it allows for the simultaneous determination of minute (multilayer to submonolayer) mass changes which accompany the electrochemical reaction with a mass sensitivity of 56.6 $Hz/microgram/cm^2$ in the present experimental configuration. Nickel films were deposited onto the QCM gold electrode either using a modified Watts bath (16) or by vapor deposition with identical results. The nickel ferrocyanide films were generated using the method of Bocarsly and coworkers (7), by maintaining the electrode potential at 1.2 V in a solution of 0.1 M KCl and 0.01 M $K_4Fe(CN)_6$ for the time required to obtain the desired film thickness. Conditions were precisely controlled to ensure uniformity of the deposited films, since this is crucial for the quantitative comparison of the QCM frequency change (which gives the mass change) to the electrochemical charge (17). FTIR microscopy (Mattson Cygnus 100 with Bach-Shearer microscope) was used to verify the film uniformity. Using a 10 micron spot size, the integrated intensity of the 2090 cm^{-1} CN stretching band was measured at several points across the face of the QCM electrode, with special attention paid to the edge region. This procedure showed that the films were uniform to

within experimental error. Following film growth, the electrochemical and QCM responses of the nickel ferrocyanide film were examined in 0.1 M CsCl solutions prepared using either H_2O or D_2O. The films were electrochemically cycled for a sufficient period (usually ca. 10 minutes) to ensure that all of the K^+ ions from the growth solution had been exchanged for Cs^+, as judged by the attainment of a constant QCM frequency for the reduced film. No interference from K^+ was observed after this procedure.

Figure 1 shows the results of such an experiment. Curves a and b in Figure 1A show that the cyclic voltammetric response is identical in these two solutions. The measured electrochemical charges are also identical, indicating that the same number of Fe redox sites are electroactive in the two solutions. The cyclic voltammetric response shown is typical of those reported for these films in Cs^+ containing electrolytes (6,7) with the exception of a somewhat larger peak to peak separation, a reminder of the sensitivity of these highly structured interfaces to the method of preparation(7). Curves a and b in Figure 1B show the QCM frequency response for these two solutions, collected simultaneously with the electrochemical data. The frequency increases during oxidation, and this increase is larger in the H_2O solution than in the D_2O solution. When the experiment was repeated in both D_2O and H_2O solutions of $CsNO_3$, identical results were obtained, providing unambiguous evidence that the observed frequency changes do not depend on the anion of the supporting electrolyte in any way.

That the frequency increases during oxidation is not unexpected, based on the earlier work of Bocarsly and coworkers (7,8). Their results indicated that the Fe(II) state of the films contained two cations per formula unit (i.e. $Cs_2Ni[Fe(CN)_6]$) while the Fe(III) state contained one (i.e. $CsNi[Fe(CN)_6]$), so that oxidation should cause the expulsion of one cation per formula unit to maintain electroneutrality. Thus, an increase in frequency resulting from the expulsion of the cations during oxidation occurs. In addition, the dependence of the frequency change on the mass of the solvent implied some degree of solvent transport during the redox event for these films. Quantitative comparison of the QCM frequency change with the electrochemical charge reveals the extent of each.

Exactly one cation should be expelled per electron removed from the film during oxidation. Direct comparison of the electrochemical charge and the QCM frequency change revealed that the mass loss (frequency increase) which

occurred during the oxidation was not sufficient to account for all of the expelled cations, i.e. a larger frequency change would have been observed if the only transport during the redox process were cation expulsion in the amount required to maintain electroneutrality. Thus, some mass must be regained by the film during or following cation expulsion to give the observed frequency change. If this mass were from solvent incorporation, then use of D_2O in place of H_2O would cause a detectable change in the observed frequency increase. Figure 2 shows a sample calculation for a typical film based on this hypothesis. Similar results were obtained for a variety of films with varying thicknesses. For this film, the calculation using the total anodic charge (2.9×10^{-3} C/cm^2) indicated that a frequency increase of 224 Hz should have been observed if the sole mass change were the expulsion of 3×10^{-8} mole/cm^2 of Cs^+. The observed frequency increases in D_2O and H_2O were 115 and 125 Hz, respectively. The discrepancies between the calculated and observed values in D_2O and H_2O were thus 109 and 99 Hz, respectively. (Given the signal to noise ratio of the measurement, the minimum detectable frequency difference is ca. 0.5 Hz.) If the entire discrepancy between the calculated frequency increase for Cs^+ and that observed experimentally were due to a net increase in the solvent content of the film, then the discrepancy for the D_2O case should have been 10% larger than that for the H_2O case because the molar mass of D_2O is larger than that of H_2O by 10%. This is exactly what was observed. The agreement is quantitative, and the requirement that the difference between the calculated mass gain due to D_2O and H_2O be 10% serves as an internal check of the veracity of the calculations and underlying assumptions. One such assumption is that D_2O and H_2O behave in chemically identical manners so that identical numbers of moles of each are transported during the two experiments shown in Figure 1. A most important assumption, crucial to the use of the frequency change in quantitative calculations (14,15), is that the film behave as a rigid layer so that the frequency change may be linearly related to the mass change. The excellent agreement presented above is unambiguous evidence of this. Feldman and Melroy (18) have previously reported rigid layer behavior for Prussian Blue films. In their study qualitative evidence for solvent transport during redox was observed.

The picture which emerges for the cesium case is that during oxidation some Cs^+ ions are expelled with a consequent influx of solvent to fill the void volume left within the lattice. During reduction, the species undergo

transport in the opposite direction, with complete reversibility of the mass changes. These data show that 3.2 moles of H_2O are incorporated when 1 mole of Cs^+ ions is expelled. Approximate molar volumes for the two species are 18 cm^3/mole (from the bulk density of water) and 12 cm^3/mole (from the ionic radius of Cs^+ of 0.169 nm given by Pauling [19]), so at first glance it seems that expulsion of one mole of Cs^+ should allow for accommodation of only 0.67 mole of H_2O. Thus, either the effective volume of Cs^+ within the lattice is considerably larger than its ionic radius would indicate, or the effective volume of a water molecule within the lattice is considerably smaller than it is in bulk water or some combination of the two. Since it is unreasonable to postulate a water density within the lattice which is enough larger (by a factor of nearly 5!) than the bulk value to account for the discrepancy, we attribute the majority of the effect to a much larger effective volume for Cs^+. Geometric arguments based on the sizes of Cs^+ and H_2O in relation to the size of the octahedral cavity [10,20-22] can be made which are in agreement with this conclusion. Briefly, even though the Cs^+ cation does not completely fill the cubic cavity (which is 0.5 nm on a side [10,20-22]), it is just large enough to preclude the presence of water molecules. Thus, void space is left within the cavity which does not have the proper geometry to accommodate the incorporation of interstitial water. A more detailed description of this 'discreteness of size' effect will be reported in a future contribution, along with a discussion of the insight provided by such measurements of solvent transport into the remarkable sensitivity of the formal potential of these nickel ferrocyanide films to the identity of the presence of various alkali metal cations.
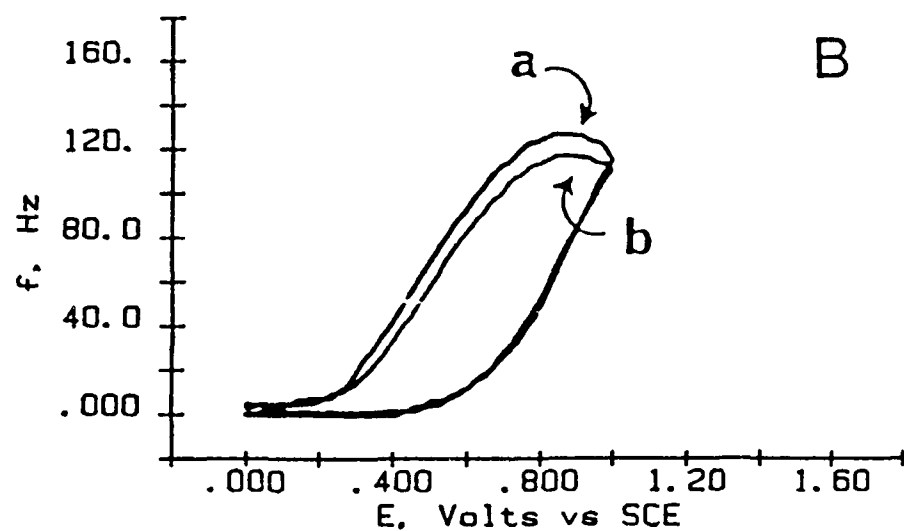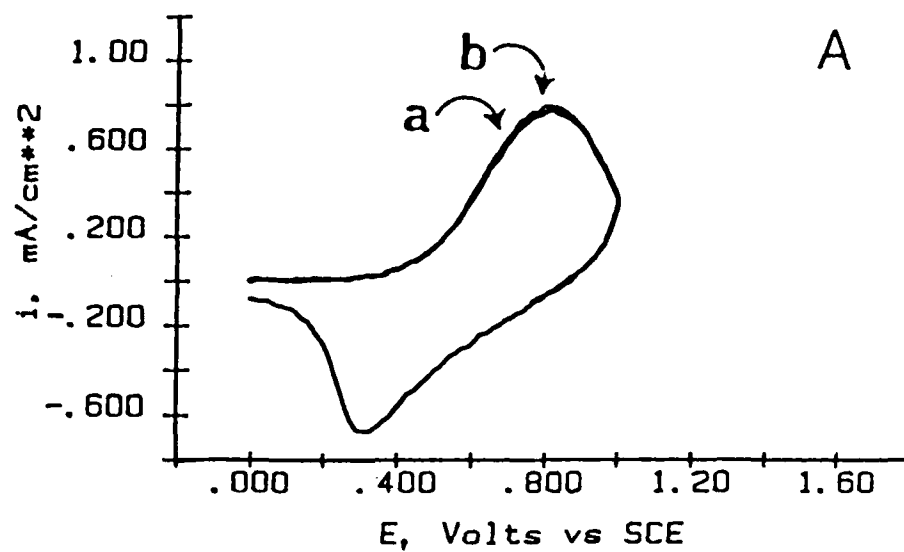
REFERENCES.
1) Murray, R. W. In "Electroanal. Chem."; Vol. 13, Bard, A. J., Ed.; Marcel Dekker: New York, 1984; p. 191.
2) a) Carlin C. M.; Kepley, L. J.; Bard, A. J. J. Electrochem. Soc. 1985 132 353-9. b) Winston, G. C.; Carlin, C. M. J. Electrochem. Soc. 1988 135 789-90.
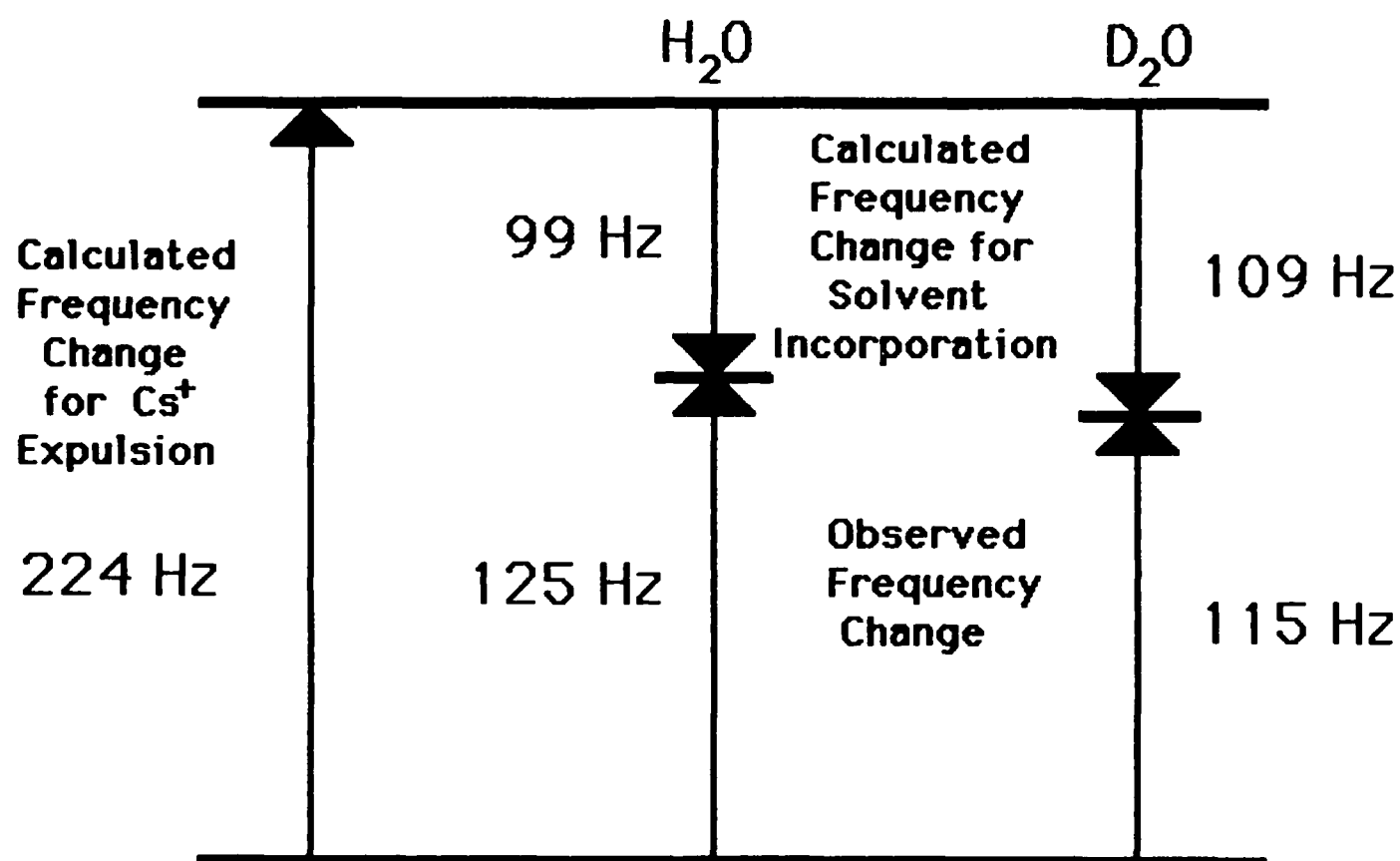3) Gottesfeld, S.; Redondo, A.; Feldberg, S. W. J. Electrochem. Soc. 1987 134 271.

4) Lewis, T. J.; White, H. S.; Wrighton, M. S. J. Am. Chem. Soc. 1984 106 6947-52.

5) Bocarsly, A. B.; Sinha, S. J. Electroanal. Chem. 1982 137 157-62.

6) Bocarsly, A. B.; Sinha, S. J. Electroanal. Chem. 1982 140 167-72.

7) Sinha, S.; Humphrey, B. D.; Bocarsly, A. B. Inorg. Chem. 1984 23 203-12.

8) Humphrey, B. D.; Sinha, S.; Bocarsly, A. B. J. Phys. Chem. 1984 88 736-43.

9) Sinha, S.; Humphrey, B. D.; Fu, E.; Bocarsly, A. B. J. Electroanal. Chem. 1984 162 351-7.

10) Amos, L. J.; Schmidt, M. H.; Sinha, S.; Bocarsly, A. B. Langmuir 1986 2 559-61.

11) Sinha, S.; Amos, L. J.; Schmidt, M. H.; Bocarsly, A. B. J. Electroanal. Chem. 1986 210 323-8.

12) Humphrey, B. D.; Sinha, S.; Bocarsly, A. B. J. Phys. Chem. 1987 91 586-93.

13) Melroy, O. R.; Kanazawa, K. K.; Gordon, J. G.; Buttry, D. A. Langmuir 1986 2 697-700.

14) Orata, D. O.; Buttry, D. A. J. Am. Chem. Soc. 1987 109 3574-81.

15) Varineau, P. T.; Buttry, D. A. J. Phys. Chem. 1987 91 1292-5.

16) Hoare, J. P. J. Electrochem. Soc. 1986 133 2491-4.

17) Ullevig, D. M.; Evans, J. F.; Albrecht, M. G. Anal. Chem. 1982 54 2341.

18) Feldman, B. J.; Melroy, O. R. J. Electroanal. Chem. 1987 234 213-27.

19) Pauling, L., "The Nature of the Chemical Bond", 3rd ed., Cornell University Press, Ithaca, N.Y., 1960, p. 514.

20) Buser, H. J.; Schwarzenback, D.; Petter, W. A. Inorg. Chem. 1977 16 2704.

21) Herren, F.; Fischer, P.; Ludi, A.; Halg, W. Inorg. Chem. 1980 19 956.

22) Ludi, A.; Gudel, H. U. Struct. Bonding (Berlin) 1973 14 1.

FIGURE CAPTIONS

Figure 1 - A) a. Cyclic voltammogram of a nickel ferrocyanide film in 0.1 M $CsCl/H_2O$ solution. Scan rate - 100 mV/s. b. Same as in (a) except that the solution contains D_2O instead of H_2O. B) a. QCM frequency response measured simultaneously with the cyclic voltammogram in (a). b. QCM frequency response measured with cyclic voltammogram in (b).

Figure 2 - Schematic representation of the frequency changes measured during the cyclic voltammogram in Figure 1. See text for details.

A

i, mA/cm**2

1.00
.600
.200
-.200
-.600

.000 .400 .800 1.20 1.60

E, Volts vs SCE

a

b

B

f, Hz

160.
120.
80.0
40.0
.000

.000 .400 .800 1.20 1.60

E, Volts vs SCE

a

b

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